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The Work Performed in Transpiration and the Resistance of Stems

By Carlton C. Curtis

It is a matter of some difficulty to make a clear demonstration of the amount of work performed by a plant in transpiration. The usual method of measuring the extent of this important operation, *i. e.*, through the lifting power of the transpiration current, is open to objection, since the stem usually allows the air to infiltrate and stop the rise of the column of mercury long before the measure of the force of transpiration has been reached.

A nearer approach to the extent of this force may be attained by subjecting a given length of the stem to pressure and forcing water through it at a rate equalling that of the transpiration stream. This may be easily accomplished, after determining the rate of transpiration with a Darwin potometer, by removing the capillary tube from the potometer and attaching it with a short piece of rubber tubing, about 20 cm., to one end of the stem, while the other end of the stem is connected with a burette by means of a longer length of tubing, so as to allow wide latitude in the amount of pressure applied. The tubings are filled with water before attachment to the stem, and care must be exercised to exclude the entrance of any air, since the latter acts as an effectual block to the passage of water. These connections are effected under water with more ease and safety from introduction of air. For short lengths of stem an apparatus stand will give sufficient elevation to the burette to furnish the necessary pressure.

The burette and tubings having been properly attached, any water that passes though the stem escapes through the capillary tube. By pinching the tube connected with the capillary tube between the fingers, a given amount of water can be forced out and absorbed with a blotter, and with the removal of the pressure the water in the tube will be drawn back. With a few trials it is possible to judge accurately just how much water to force out in this way, so that the capillary tube will be left nearly empty upon releasing the pressure. The water passing through the stem will cause the water to flow again through the tube, and the current may be timed over the same course as in the transpiration tests. The base of the capillary tube is attached to the rubber tubing in order that the same lapse of time may intervene before measuring the rate as is utilized in the measurements with the potometer. It is important that no more water than the volume of the capillary tube should be forced out, otherwise air will be drawn back into the rubber tube and introduce sooner or later troublesome Jamin's chains in the tests. While it is feasible to test only short lengths of stems by this method, the considerable resistance offered by such pieces gives a very striking and accurate basis for an estimate of the work performed in transpiration. The objection might be raised that in subjecting stems to pressure in this way histological elements would become active in the transmission of water that were functionless in transpiration. While it must be conceded that all cells may not be equally active or are quite functionless, in such stems as may be tested by a potometer, we are dealing with only a few annual zones of growth—frequently but one—and therefore no considerable error is encountered from this source. The demonstration by Strasburger that at least several annual zones assist in transpiration, as may also readily be observed in sections of stems that have imbibed colored solutions, renders it possible that under the pressures required for short sections of most woody plants the ordinary conducting cells are alone active in the transmission. In the case of some stems of high resistance, noticeably succulents, it is very obvious that a pressure that will force water through the stem at a rate equalling that of transpiration causes a considerable exudation from the extra-xylar tissues of the pith and cortex. In such cases, certainly, the action of these normally feebly transmitting cells would lower somewhat the resistance encountered by the passage of water through the xylem.

I.

	1	2	3	4		1	2	3	4
Abutilon	48	45	49	10 × .8	*Acalypha*	13	13	29.5	10 × .5
	46	45				12	13		
	47	46				13	13.5		
	48	47				13	14.5		
	48	48				13.5	16		
	48	48				13.5	17		

Abutilon	63.5	65	41	10 × .7	*Acalypha*	48	47	32	10 × .8
"	2^{27}	2^{28}	20	10 × 1.0	"	63	65	26	10 × .9
"	1^{58}	2^{56}	28	10 × .7	*Salix*	6	7	53	10 × 1.0
"	1^{34}	1^{36}	38	10 × .8	*Ailanthus*	8	7	29	10 × .9
Taxus	1^{20}	1^{19}	48	10 × .8	*Cornus*	7.5	6.5	71	10 × .9
	1^{22}	1^{21}				8	7		
	1^{21}	1^{20}				8	7		
	1^{20}	1^{22}				7	8		
	1^{21}	1^{23}				7	8.5		
	1^{21}	1^{23}				8	9		
Taxus	3^{50}	3^{45}	25	10 × .6	*Cornus*	13	13	39	10 × 1.0
"	2^{40}	2^{43}	42	10 × .6	"	12	13	51	10 × .8
"	12	12	105	10 × 1.0	"	13	14	48	10 × .7
"	59	58	52	10 × .8	*Viburnum*	73	71	38	10 × .6
						36	38	64	10 × 1.0

The experiments given in the first table are examples from a great number that have been performed in our laboratory and are representative of the variation and extent of the resistance that the transpiration current must overcome. The stems were usually tested after standing over night in water or less commonly three or four hours in water. In the first column opposite the name of the plant is recorded the transpiration rate. In four examples, *Abutilon*, *Acalypha*, *Taxus* and *Cornus*, six consecutive readings are given to show the variations that are characteristic of the transpiration rate when conditions are as constant as possible and for comparison in the second column are six readings from a length of stem under pressure. In the other examples averages only of a series of readings are given. The pressure required to produce the rate approximating that of transpiration is found in the third column and in final division are the dimensions in cm. of the stems subjected to the pressure. In the majority of these and subsequent experiments filtered tap water was used and fresh cuttings of the ends of the stems were made in setting up the experiments if any considerable lapse of time intervened sufficient to produce a marked variation in the readings. In the case of stems under pressure this was very quickly effected, and distilled water gave the same though slower declines. This difference in the rates of consecutive readings shown in columns 1 and 2 are rather suggestive of the processes employed in maintaining the current in transpiring stems. Pressures result in a fairly constant rate. The same is true of suction. In some of the experiments under discussion, also in tables 2 and 6, the pressure was replaced by attaching the stems to an air pump and recording the amount of suction required to draw water through the stem at the transpiration rate. The results are the same in either case. The transpiration current is an irregular one not indicative of a pull or pressure while the distribution of water in the stem can hardly be reconciled with the existence of such a condition.

Another interesting feature is the wide variation in the resistance of the stems, not alone of various plants but of the same species.

The tests were made on vigorous stems, entirely free of branches below, such as may be obtained from vigorous plants. In such cases the wood is exceptionally regular owing to the early suppression of all lateral organs. In some instances, however, the cause of the variations of rate was apparent, on splitting the stems, in irregularities of growth due to branching or other causes. The presence of these resistances becomes more apparent if transpiring stems are allowed to imbibe solutions of eosin when the difficulty of the fluid in passing the nodes or any obstruction due to irregularities in the grain of the wood is very apparent. More frequently the cause of the resistance cannot be accounted for on this ground and must be due to the specific pecularities of the individual elements rather than to any grouping of tissues that is apparent to the eye. Such may be the explanation of the high resistance of *Pelargonium* for there is sufficient carrying capacity in the water conduits to render unnecessary the high pressure required.

While as a rule the resistance increases with the rate there is no regularity in this ratio, as will be noted in comparing the second and third columns. However, it is to be noted that when a given pressure produces a certain rate of flow any increase or decrease of pressure causes about the same fluctuations of rate as would be found in capillary tubes. Two examples will illustrate this relation, the first number to the left being the pressure and the succeeding ones in the same line the rate of transmission.

Acalypha	24	63	63	64	65	65	*Taxus*	58.6	61	61	61	62	62	63
	30	55	55	56	56	57		68.6	51	51	51	51	52	52
	36	48	48	48	49	49		78.6	45	45	44	45	46	46
	42	42	43	43	44	44		48.6	77	77	77	77	78	78

RELATION OF LENGTH TO PRESSURE

The following experiments illustrate the variations in resistances of different portions of the same stem. As in the first table the transpiration rate follows the name of the plant, in the second column is the rate obtained by pressure, next the pressure employed and the dimensions of the stem. Columns 5, 6 and 7 give the rates when $\frac{1}{4}$, $\frac{2}{4}$ and $\frac{3}{4}$ respectively of the stem had been removed.

II.

	1	2	3	4	5	6	7
Abutilon	38.5	42	79	40 × 1.1	32	27	23
	40	42			32.5	26.5	23
	41	42.5			32.5	27	23.5
	39	42.5			32	27.5	23
	39.5	43			32.5	27.5	23
	40.5	43			32	28.1	25.5
Abutilon	2^{1}	1^{58}	66.5	40 × .9	52	20	15
"	1^{47}	1^{43}	37.4	40 × .8	1^{26}	58	34
Syringa	60	61	220	40 × .8	34	30	15
	58	61			34	31	16
	56	63			35	31.5	16
	59	64			35	31	17
	58	64			36	31.5	18
	58	64			39	32	18
Syringa	58	61	190	30 × 1.0	43	30	21
"	4^{50}	4^{50}	103	30 × 0.6	2^{30}	1^{20}	40
Viburnum	63	58	195	40 × .6	43	39	16
	61	58			44	40	15
	60	59			43	38	15
	59	60			41	39	16
	62	59			41	38	16
	61	59			40	39	16
Viburnum	56	65	186	40 × 1.0	20	16	9
"	48	48	222	40 × .9	31	20	15
Pelargonium	1^{5}	5^{37}	186	40 × 1.0	2^{34}	1^{27}	1^{4}
	1^{9}	5^{52}			2^{34}	1^{28}	1^{5}
	1^{6}	6			2^{35}	1^{26}	1^{6}
	1^{10}	5^{58}			2^{37}	1^{27}	1^{6}
	1^{8}	5^{56}			2^{38}	1^{28}	1^{7}
	1^{5}	5^{56}			2^{38}	1^{28}	1^{8}
Pelargonium	1^{50}	3^{56}	186	40 × .9	2^{12}	42	23
"	1^{22}	3^{10}	186	40 × .8	2^{26}	1^{58}	1^{38}
"	1^{20}	1^{24}	186	20 × 1.0	47	26	14

Here again it is evident that only in the remotest way is there any conformity to the law of Poiseuille for capillary tubes, at least the ratio of rate, length, radius and pressure can hardly be said to show a variation in conformity to this law. Some stems offer a resistance out of all proportion to their dimensions and the volume of transpiration. *Pelargonium* is a striking example of this. It is possible that this may be due in part to blocking by substances escaping from the cut stems. In other instances equally striking examples are sometimes met, the pressures ranging from .08 to .2 of an atmosphere per sq. cm. in the short lengths of stems mentioned above. The irregularities shown in the 2d, 5th, 6th and 7th columns of the first experiment with *Viburnum* are doubtless due to the fact that the negative pressure was not satisfied. It was frequently noticed in such cases and particularly with stems tested in the winter that they would show for hours an irregularity and even an acceleration of rate. The rapid decline in the rate in the short lengths is, of course, due to increased volume transmitted.

Electrical Currents and Conductivity

In some work, conducted two years ago at the Physical Laboratory, a slight difference of potential was shown to exist between the top and bottom of trees. Haacke has also demonstrated the presence of weak currents circulating in the plant cells. In view of these facts and the marked effect of electrical currents upon plants, lengths of stems under pressure and also transpiring stems with potometer attached were submitted to currents from a double 18-inch plate, Winshurst static machine and also to the street current, 110 volts. The current was applied to the stems by removing two strips of the cortex 10 cm. apart and wrapping the electrodes about the wood.

III.

	C		C			RC		RC
Acalypha	39	39.5	42	39.5	52.5	54	54	56
	39.5	40.5	41.5	40.5	53	53	56.5	55
	39.5	40.5	42	40.5	54	53	57	54.5
	39	41.5	39.5	40.5	54	51	56	54
	39	41.5	39	41	54.5	51	57.5	53
	38.5	42	39.5	41.5	55	51	57.5	54
	38	42	38					

		C		C		C		C		C.
Abutilon	57	55	60	57	63	59.5	1^{40}	2^{29}	2^{34}	2^{31}
	56	55	60	57	62	60	1^{50}	2^{30}	2^{31}	2^{30}
	57	54	60	56	61	58	2^{20}	2^{28}	2^{29}	2^{29}
	57	54	61	56	61.5	59	2^{22}	2^{27}	2^{32}	2^{29}
	56.5	54.5	61	56	62	58.5	2^{25}	2^{26}	2^{35}	2^{30}
	57	54	62	55	62	59	2^{26}	2^{26}	2^{36}	2^{30}

The columns marked C give the rate with the current on, RC with the current reversed, those unmarked without the current.

The results as far as showing any effect upon the conductivity of the xylem is negative. The current from the static machine and also weak dynamic currents had no effect.

The variations in the above examples which are taken from experiments with street current are due to the high resistance of the stem to the current. This resulted in a rise of temperature and the change of rate. The records of temperature in the preceding work have not been given inasmuch as the examples selected for illustration have not been subjected to any variations in this respect that are of importance. In the test upon *Abutilon*, for the purpose of producing variations in the conductivity of the stem, a 1% NaCl and an isotonic cane-sugar solution were used in place of water, the measurements with the latter occurring in the four right-hand columns. The results are the same as with water.

SALT SOLUTIONS AND RATE

The marked influence of salt and sugar upon the rate in the last experiment led to some further tests for the purpose of determining if there was any specific peculiarity in the cell wall that might be revealed by the rate of transmission. Solutions of $ZnCl_2$ and sugar were prepared isotonic with a decinormal solution of NaCl and stems were subjected to these different solutions under constant pressure.

IV.

	H_2O	NaCl	H_2O	$ZnCl_2$		H_2O	NaCl	H_2O	$ZnCl_2$
Taxus	2^{34}	2^{20}	2^{24}	2^{18}	*Acalypha*	1^{20}	52	64	61
	2^{34}	2^{21}	2^{25}	2^{21}		1^{19}	52	69	59
	2^{34}	2^{32}	2^{32}	2^{31}		1^{18}	51	70	59
	2^{35}	2^{35}	2^{34}	2^{40}		1^{18}	50	72	62
	2^{35}	2^{34}	2^{35}	2^{34}		1^{19}	49	74	63
	2^{35}	2^{34}	2^{40}	2^{36}		1^{18}	49	78	63

	H_2O	$C_6H_{22}O_{11}$	H_2O	NaCl
Taxus	33	48	53	50
	33	54	54	50
	33	58	56	51
	34	61	60	51
	33	73	61	50
	33	74	62	51

	H_2O	$C_6H_{22}O_{11}$	H_2O	$ZnCl_2$
Acalypha	50	52	62	59
	51	54	63	58
	51	61	62	58
	52	62	62	62
	52	63	63	62

The few examples here given are typical of the variations resulting upon a change of solution. The results seem to indicate that in the case of NaCl and $ZnCl_2$ there is not apparent any specific relationship between the wall and any of the substances different from that existing between the wall and water. Investigations upon this point have not been completed. The accelerating effect following the substitution of salt solutions for water appears to be due to the osmotic action of the two fluids thus brought together acting through the walls of the living cells. The fact that the rate often accelerated for some time but finally declined would indicate this relation. It is not probable that the dead cells play any rôle in the acceleration of the rate. The measurements with sugar, however, indicate that the molecules are not freely transmitted and so act as an effectual block to any osmotic action while the introduction of another solution would tend to remove the obstruction and allow a renewal of osmotic action in the cells. This result would appear to throw considerable light upon the manner of transmission of sugars through the stem and account for their meager occurrence in the sap.

Solutions of 50 per cent. alcohol had a very marked effect upon the conductivity of the cells, causing a marked and rapid decline which was not changed with the introduction of water. Thus with a rate of 46, 46, 47, 47, 47 under water pressure, with alcohol the readings were 60, 61, 63, 63, 64, followed with water 82, 83, 84, 85, 85. The results are evidently due to a molecular change in the walls whereby their power of transmission has been materially interfered with. The feeble attraction between the alcohol and the molecules of the cell wall would tend to prevent imbibition and doubtless leaves them less attractive to water.

TEMPERATURE AND RESISTANCE

For the purpose of comparison with effects upon capillary tubes, observations were made upon the action of temperatures on the conductivity of stems. In the first example the stem above the potometer for about 35 cm. was covered with a layer of snow about 2 cm. thick and bound with sheet rubber so that there could be no drip upon the potometer. A thermometer was placed among the leaves, 5 cm. above the jacket of snow in order to determine whether any variation of rate could be explained by a lessened action of the transpiring organs rather than by the increased resistance of the stem. The snow was applied for about one half hour, producing a fall of temperature among the leaves of only 2.8 degrees. The wide variation from the normal transpiration rate of 16.4 to 36.2 cannot of course be attributed to so slight a fluctuation of temperature and the delayed approach to the normal rate also clearly indicates that the greatly reduced temperature of the stem is the chief factor in the reduction of the rate. It is apparent that the wide variation is not at all in keeping with the fluctuations to be noted in capillary tubes and the marked changes of rate may probably be accounted for as principally due to reduction in the size of the cell cavities.

V.

Abutilon	16	12^{50}	20.5°	19.6	1^{10}	18.6°	35	1^{25}	17.7°	34.6	1^{40}	19.4°
	16 8			20.2			36.2			33.8		
	16.5			21			36			34.5		
	16			22.5			37			33.4		
	16.4			23			36.4			32		
Citrus	25	11^{20}	18.3°	28.	11^{45}	15.5°	33.5	12	16.5°	27	12^{20}	19.4°
	26			28.6			33.5			26		
	25.6			31.			33.5			25		
	26.2			32.			33			25.5		
	26			32.5			33			24.		
Abutilon	55	2^{20}	23°	1^{20}	2^{30}	8°	1^{25}	2^{50}	20.6°			
	56			1^{33}			1^{20}					
	56			1^{35}			1^{11}					
	57			1^{34}			1^{6}					
	56			1^{34}			1^{2}			22		
Abutilon	54.3	3^{15}	24.7°	1^{10}	3^{40}	8°	1^{14}	3^{50}	12°	13	4^{20}	21°
	54.5			1^{13}			1^{8}		14°	1		23°
	55			1^{15}			$1^{8,5}$			58		
	54.5			1^{18}			1^{7}			58		
	54.5			1^{19}			1^{6}		16°	56		24°

The branch of *Citrus* was treated in the same way, about 20 cm. of the stem being covered with snow, with practically the same results. It is to be noted that the rise of temperature in the room during the experiment was sufficient to cause a much quicker acceleration of rate than in the preceding example.

In the third experiment a length of stem immersed in water at 23° was tested under pressure. The rate of 55.8 was lowered, when the stem was covered with water at 8°, within five minutes to 1^{20}, and dropped rapidly to 1^{34}. Water at 25° was now introduced and the first measurement a few minutes later showed a rate of 1^{25} followed by a sharp rise. The temperatures given are probably near those of the stem since the thermometer was lying in the dish against the stem and they would not vary materially in taking on the temperature of the surrounding media. The final test illustrates the variations of rate at different temperatures. The readings are not consecutive. The results are rather suggestive as indicating the very considerable additional work placed upon the plant by variations of temperature. These changes are often sudden and not only act upon the transpiring organs but also introduce a very considerable resistance that is frequently overlooked.

RESISTANCE INTRODUCED BY CUTTINGS

The localization of resistances noted above led, for the purpose of comparison, to measurements on the effect of the introduction of resistances by cutting. The tests were confined to *Taxus* as these plants will better stand the treatment without flagging. In the first column is given the transpiration rate of the branch and in the second and third columns the rates when the stem was cut ½ and ¾ through. The fourth column shows the rate when the column was reduced to a few sq. mm., indicated at the right of the column.

VI.

					sq. mm.						sq. mm.	
Taxus	8	9	14	13	6	9.5	24	12	19	29	8	8 × 1.5
	8.1	9.5	13.5	12.8		10		14	20	34		
	8	8.9	13.2	12.2		9		16	20	34		
	8.4	8.4	13	13		9		16	20	37		
	8	8.9	13.6	13		10		15	21	36		
	8.2	9	12	13		10.5		14	22	37		
Taxus	28.5	29.5	30.8	35	2	29	15	44	90	184	7	7 × .9
	28	29	30.4	36		30		45	98	196		
	29.2	29	30	35		29.5		48	102	186		
	28.5	28.5	30.1	39		29.5		46	96	200		
	28.4	29	29.5	36		30		47	98	189		
	28.5	28.5	30	36		29		46	98	198		

Taxus	6.7	8	13.6	15.5	9	7.2	58	15.6	34	52	8	7 × 1.0
	7	7.5	13.9	15.5		7.2		17	36	58		
	6.8	7.5	12.2	16		7.4		18	36	59		
	7	7 2	13.8	15.6		7.4		17	35	59		
	7.2	7.1	12	15.1		7.4		18.2	37	60		
	7.2	7.1	11.6	15.6		7.4		18.5	36	61		

The second part of the table gives the results when lengths of stems under pressure were treated in the same way. The number to the right of the first column indicates the pressure required and the three succeeding columns record the results of cutting ½ and ¾ through and to a few sq. mm. The final numbers give the dimensions of the stem. The lengths of these stems also indicate the distance above the potometer at which the cuttings were made.

These cutting experiments of Dufour are among the most important that can be performed in transpiration since they give a very clear demonstration of the vital action of the living cells in maintaining the transpiration stream. The recovery from the effect of cutting noted in the first part of the table is entirely done away with in the second series of measurements upon the stems under pressure. In fact the results in this latter case are practically the same as those obtained in the different lengths of stems in Table II. These results were certainly not to be expected and may be accounted for, I believe, on the ground that the velocity of the fluids at the point of cutting is so enormously increased that a resistance is generated quite out of proportion to that acting on the stem at the normal rate and sufficient to reduce the rate practically to that of stems increased in length in proportion to the depths of cutting.

RELATION OF CONDUCTING AREA IN STEM TO VOLUME OF FLUID

The ability of the plant to maintain the water current unchecked through so small an area of stem led to some investigation upon the extend of the area at the disposal of the plant for the conduction of fluids and the precentage of this space actually utilized. To determine the percentage of cavity in the stem microscopic cross sections were prepared and areas, representative of the various growths of the stem were drawn on sheets of tinfoil with a camera lucida. The weight of the areas bearing the tracings of the wood sections having been determined, by cutting out the lumen of the cells and determining their weight, the percentage of cavity could be determined. This appears to be fairly accurate. The tinfoil selected showed but slight variations in weight and the tracings, cutting and weighing can be made with accuracy. In the following experiment with *Acalypha* a potted plant was placed in a glass jar and the mouth of the jar covered so as to prevent evaporation from the soil. The amount of transpiration for two hours was found to be at the rate of 7.1 grm. per hour. The stem was then cut under water and allowed to stand three hours. It was then allowed to absorb water from a florence flask plugged with cotton for two hours, the loss per hour being 4.53 grm. The stem being transferred to a solution of eosin for one hour the ascent of the fluid wâs found to be 75.4 cm. From cross sections of the stem the following area of lumen and percentage of cavity was obtained:

Weight of area adjoining pith	3.030	
" " cavity in this area	1.726	Percentage of cavity 56.9
Weight of area in middle of xylem	3.047	
" " cavity in this area	1.709	Percentage of cavity 56.1
		Average 56.5.

The area of the cross section of the stem was 23.15 sq. mm. This would give a water conduit of 13.08 sq. mm.

It is interesting to note the relation of this latter area to the rise of eosin in the stem and the absorptions both in the case of the cut and uncut stem. Taking the rise of the eosin, 75.4 cm. as an approximation of the rate of absorption of the cut stem it is seen that only 6.01 sq. mm. would be required to carry 4.53 grm. to a height of 75.4 cm. Considering the absorption of the uncut branch if the entire area at the disposal of the stem for the conduction were utilized the 7.1 grm. would rise only 54.2 cm.

Two similar tests were made on *Abutilon*. The potted plant transpired 3.25 grm.; cut, 2.95 grm. per hour. Percentage of cavity, 50.1. Area of wood, 37.75 sq. mm. Area of cavity 18.91 sq. mm. 3.25 grms. would consequently rise 17.18 cm. if entire area was utilized. Recorded rise of eosin, 23.5 cm. This would require an area of 13.84 sq. mm.

Another plant transpired 4.73 grm.; cut, 3.9. Percentage of cavity, 55.6. Area of wood, 47.56. Area of cavity, 26.45. This would necessitate a rise of only 17.5 cm. while the eosin solution reached a height of 43.4 cm., requiring an area of 10.1 sq. mm.

A branch of *Taxus* was tested in the same way. Measurements of different sections from the cross section of the stem gave exceptionally uniform results. The area of the wood, 29.3 sq. mm. Percentage of cavity 35.5. Area of cavity, 10.40 sq. mm. Absorption by stem 2.19 grm. The rise therefore would be 20.2 cm. Recorded rise of eosin 31 cm.; necessitating an area of 6.77 sq. mm. It should be stated that the above-mentioned tests were made on plants with small transpiring leaf areas, as the amount of absorption indicates.

It will be seen that the percentages secured in these experiments correspond in the main with results obtained by Rb. Hartig and Sachs and it would appear that there is less opportunity for the introduction of error in this method while in addition the directness of obtaining the results renders the process more available than the specific gravity method.

It is very evident that the carrying capacity of the water conduits is greatly in excess of any demands made upon it by the plant and it is reasonable to suppose that the proportions expressed above between the volume of water and the area of cavity of the stems fairly represent the conditions that obtain in these plants. It will be noted that the percentage of air space is not necessarily larger in the more actively transpiring plants. These relations render quite unnecessary the supposition of Vines that the walls under certain conditions may serve as channels in the transmission of water.

SUMMARY

By means of pressure tests a definite measure of the resistance of a given length of stem to the transpiration current may be obtained and the work actually performed by the plant can be computed. More frequently in the case of small plants by the lifting method of measuring this force a partial estimate of what the plant can do rather than what it is doing is obtained.

The resistance overcome by the transpiration current is often much higher than can be measured by the suction of the transpiring shoot and is subject to extensive variations in different species of plants and among plants of the same species. Various parts of a stem differ widely in the resistance offered and consequently there is no ratio in the rate of transmission of a stem under pressure and the length of stem.

The rate of transmission is not affected by electric currents and various solutions as in capillary tubes. The former has no effect while the relation of the character of the wall to the nature of the solution may have a marked effect in the rate of transmission. Changes of temperature produce marked fluctuations in the amount of resistance, due largely to variations in the lumen area of the cells.

Partial severing of the water conduits by cuttings does not produce variations in the rate corresponding to those brought about by constricting the bore of tubes at a given point. On the contrary the resistances so introduced are practically equivalent to an increase in the length of the stem proportional to the extent of the cutting. Only a portion of the lumen area is utilized by the plant. This condition may be maintained within certain limits either in slowly or actively transpiring plants through variations in the rate of transmission.